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Evaluating environmental benefits of low-cost biogas digesters in small-scale farms in Colombia: a life cycle assessment

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Abstract

The aim of this study was to assess the environmental benefits of implementing low-cost digesters in small-scale farms in Colombia by using the LCA methodology. Four scenarios were taken into account considering two small-scale farms located in different areas: two (previous) scenarios where manure was stored in a manure pit and liquefied pretroleum gas (LPG) was used for cooking; and two (current) scenarios where manure is treated in low-cost digesters, the digestate replaces the synthetic fertiliser and the biogas is used for cooking replacing the LPG. Results showed that digesters implementation considerably reduced (by up to 80%) potential environmental impacts associated with manure handling, fuel and fertiliser use in the small-scale Colombian farms. This was mainly due to the reduction of LPG and synthetic fertiliser use which were replaced by biogas and digestate. An economic assessment showed that low-cost digesters reduced expenses associated with cooking fuel and fertiliser purchase by 80%.

Keywords: Anaerobic digestion; Biogas; Environmental impacts; Life cycle assessment; Small-scale digester; small-scale farming

1. Introduction

In rural areas of Colombia, around 50% of the population lives below the poverty threshold and the economy is mainly based on self-sufficient agriculture and family farming (World Bank Group, 2018). In these areas, the poorest households rely on traditional fuels, such as firewood and dried dung, to meet their daily heating and cooking needs. On the other hand, liquefied petroleum gas (LPG) (e.g. propane gas) is the fuel of choice for those to whom it is available and affordable (i.e. small-scale farmers) (World Bank Group, 2014). In particular, private companies initiated large-scale programs subsidizing the adoption of LPG in rural areas, thereby increasing their customer base (Global Alliance for Clean Cookstoves, 2012). Currently, the use of LPG represents around 40% of the energy supply mix for cooking in rural areas of Colombia (Global Alliance for Clean Cookstoves, 2012). Nonetheless, there are drawbacks to accessing this energy fuel, such as purchasing (50 dollars per month on average), transporting costs from urban to rural areas (25 dollars per month on average), and risk in propane tank management (Castro et al., 2017a).

Moreover, in small-scale Colombian farms livestock waste (i.e. manure) is not properly managed, which is responsible for environmental impacts such as odours, greenhouse gas (GHG) emissions, water and soil pollution. Usually, manure, which could be transformed into biofertiliser, is piled up without any further treatment. Inappropriately handled livestock waste, not only causes severe air, land and water pollution, but also generates diseases affecting both animals and human beings caused by pathogen microorganisms contained in manure (WSPA, 2011). On the other hand, synthetic fertiliser, which is very expensive for small-scale farms, is generally used to improve crops productivity.

In this context, low-cost biogas plants are a good candidate for reducing environmental impacts and improving the standard of living of rural families. Low-cost digesters are considered a clean and environmentally friendly technology which can help small-scale farmers to treat livestock waste in a sustainable way, while producing a biofertiliser (digestate) and meeting their energy needs (i.e. by providing biogas) (Garfí et al., 2016; Kinyua et al., 2016; Rajendran et al., 2012).

Thanks to their technical, socio-economic and environmental benefits, rural biogas plants have been spreading in Colombia since the 1980s. In particular, the plastic tubular digester is the most common digester model due to its low-cost and ease of implementation and handling, since it does not require specialised skills for the construction and maintenance (Garfí et al., 2011a).

A few studies assessed the environmental benefits of low-cost digesters implemented in rural areas of low-income countries, such as Peru, China, India, Vietnam and Ethiopia. These studies proved that low-cost digesters led to environmental benefits by reducing GHG emissions, soil and water pollution (Garfí et al., 2012; Lansche and Müller, 2017; Sfez et al., 2017; Vu et al., 2015; Wang et al., 2018).

The aim of this study was to assess, for the first time, the environmental benefits of implementing low-cost digesters in small-scale farms in Colombia by using the Life Cycle Assessment (LCA) methodology. To this aim, four scenarios were taken into account considering two small-scale farms: two (previous) scenarios where manure was stored in a manure pit and LPG was used for cooking; and two (current) scenarios where manure is treated by using low-cost digesters, the digestate replaces the synthetic fertiliser and the biogas is used for cooking replacing the LPG. Additionally, an economic evaluation was also addressed in order to assess the feasibility of this technology in small-scale Colombian farms based on the costs and benefits related to it.

2. Material and Methods

2.1 Low-cost biogas digesters description

The two low-cost biogas plants considered in this study are tubular plastic (i.e. polyethylene) digesters implemented in two small-scale farms in Colombia. The first small-scale farm is located in the Caribbean region (0 m.a.s.l), while the second one is located in the Andean region (950 m.a.s.l) (average ambient temperature 30 and 23 ºC, respectively).

Plastic tubular digesters consist of a tubular polyethylene bag placed into a trench (An and Preston, 1999). A simple roof is used to cover and protect the plastic bag. Diluted feedstock flows through it from the inlet to the outlet. They are neither mixed nor heated. The biogas is accumulated in the upper part of the bag and collected by means of a gas pipeline connected to a reservoir, and then to the cookstoves (Castro et al., 2017a, 2017b).

Both digesters treat 50 kg of cow manure per day, which corresponds to the waste generated by 3 cow heads that stay in sheds around 60% of the time (Castro et al., 2017a, 2017b). Since design criteria for the digester depend on each location, the two biogas plants have different hydraulic retention times (HRTs) and, thus, different volumes. Indeed, in the case of the small-scale farm implemented in the tropical region (i.e. mesophilic conditions), a low HRT (28 days) is used. On the other hand, at high altitude (i.e. psychrophilic conditions) a longer HRT of 35 days was chosen. Thus, the former digester has a smaller useful volume compared to the latter (4 vs. 7.5 m^3 for the digester implemented in the Caribbean and Andean region, respectively). Thus, the amount of digestate produced is higher in the digester implemented in the Andean region (i.e. around 140 and 200 L/day for the digester implemented in the Caribbean and Andean region, respectively). Since anaerobic digestion performance strongly depends on temperature, biogas production is different in both cases. Indeed, the biogas production rate is higher in the Caribbean region compared to the Andean region (0.23 vs. 0.11 $m^3_{biogas}/m^3_{digester}\cdot day$, respectively). Methane content is around 65% in both cases. Thus, biogas production covers 100% and around 95% of fuel needs for cooking in the former and latter case, respectively (Castro et al., 2017a, 2017b).

2.2 Life Cycle Assessment

LCA is a comprehensive, systematic and standardised methodology for estimating the potential environmental impacts of a product, process or activity using a cradle to grave approach (ISO, 2000; ISO, 2006). The environmental impacts are evaluated by identifying and quantifying energy and materials used and wastes released to the environment through the whole life-cycle. LCA consists of four main steps: i) goal and scope definition, ii) inventory analysis, iii) impacts assessment and iv) interpretation of the results (ISO, 2006). The following sections describe the specific content of each step.

2.2.1 Goal and scope definition

The goal of the LCA was to assess the environmental impacts of low-cost digesters implemented in two small-scale farms in Colombia. As mentioned above, the first small-scale farm is located in the Caribbean region (0 m.a.s.l), while the second one is located in the Andean region (950 m.a.s.l). In order to evaluate the environmental benefits of low-cost digesters, the scenarios previous to digesters implementation were also taken into account. Thus, the following scenarios were considered:

1) Scenario 1: previous scenario in the small-scale farm located in the Caribbean region, where manure was stored in a manure pit, LPG was used for cooking and synthetic fertiliser was applied to crops.

2) Scenario 2: low-cost digester implemented in the small-scale farm located in the Caribbean region (mesophilic conditions), where the digester treats manure and produces biogas. The digestate replaces the synthetic fertiliser, while the biogas is used for cooking replacing the LPG.

3) Scenario 3: previous scenario in the small-scale farm located in the Andean region, where manure was stored in a manure pit, LPG was used for cooking and synthetic fertiliser was applied to crops.

4) Scenario 4: low-cost digester implemented in the small-scale farm located in the Andean region (psychrophilic condition), where the digester treats manure and produces biogas. The digestate replaces the synthetic fertiliser, while the biogas is used for cooking replacing the LPG.

Two functional units (FUs) were taken into account. First of all, the environmental impacts were referred to 1 kg of treated manure, in order to evaluate and quantify the benefits of the digesters (current) scenarios (scenarios 2 and 4) compared to the manure pit (previous) scenarios (scenarios 1 and 3). In this case, the main function of the system was to treat livestock waste. Subsequently, in order to enable the comparison between scenarios 2 and 4 (i.e. mesophilic vs. psychrophilic conditions), 1 m^3 of biogas (under standard conditions) was used as FU. In this case, the main function of the systems was to produce biogas for cooking.

The system boundaries included: air and soil emissions due to manure storage; LPG production and transport (20 km for both scenarios); air emissions due to LPG combustion; synthetic fertiliser production and transport (20 km for both scenarios); direct emissions to air and soil due to synthetic fertiliser and digestate application to soil; materials for digesters construction and maintenance; rainwater consumption and air emissions due to biogas losses and combustion.

2.2.2 Inventory analysis

Inventory data for the investigated scenarios were taken from Castro et al. (2017a and 2017b) and are summarised in Table 1, 2 and 3. In the case of previous scenarios (scenarios 1 and 3), LPG consumption accounted for 18 m^3 per month (under standard conditions), which corresponds to the cooking need for five people and five hours per day (Castro et al., 2017a, 2017b). The amount of synthetic fertiliser considered refers to the nutrients requirements of potato crop per hectare (N: 85 kg/ha; P_2O_5: 175 kg/ha; K_2O: 40 kg/ha), which is the most common crop in rural areas of Colombia (FAO, 1992). An average distance of 20 km was considered for LPG and synthetic fertiliser transportation from urban areas to the small-scale farms. Direct emissions to air and soil (i.e. nutrients leaching) due to manure storage were calculated using emissions factors from the literature (i.e: CH_4: 6.6 mg/kg_{manure} per day; NH_3: 12.5% of the initial N content; N_2O: 1.5% of the initial N content; N: 20% of the initial N content; P: 30% of the initial P content; K: 50% of the initial K content) (Gupta et al., 2007; Pardo et al., 2015; Reddy et al. 2010; Sfez et al., 2017). Manure nutrients content was taken from the specific case studies (Castro et al., 2017a, 2017b). Similarly, direct indoor emissions from LPG combustion were estimated considering emissions rates from previous studies (i.e. CO_2 (fossil): 3085 g/kg_{LPG}; CO (fossil): 14.9 g/kg_{LPG}; CH_4 (fossil): 0.05 g/kg_{LPG}; NMVOC: 18.8 g/kg_{LPG}; NO_X: 3 g/kg_{LPG}; N_2O: 0.15 g/kg_{LPG}; PM2.5: 0.3 g/kg_{LPG}; PM10: 1.1 g/kgLPG; SO_2: 0 g/kg_{LPG}) (Grieshop et al., 2011; Majumdar et al., 2013; Sfez et al., 2017; Venkataraman et al., 2010). Nitrogen emissions to air due to the application of synthetic fertiliser on agricultural land were based on IPCC (2006) (i.e. 25% and 1% of the initial N content for NH_3 and N_2O, respectively). Emission rates to estimate nutrients leaching due to synthetic fertiliser application in the field were the same as for manure storage (Reddy et al. 2010).

In the case of digesters scenarios (scenarios 2 and 4), the type and amount of construction materials were calculated considering biogas plants characteristics and design (Castro et al., 2017a, 2017b). The considered lifespan was 20 years for all materials, except for plastic which was reduced to 5 years (Pérez et al., 2014). As mentioned above, biogas completely replaces LPG consumption in scenario 2 (i.e. digester implemented in the Caribbean region), while a small amount of LPG (around 5% of the fuel requirement for cooking) is still used in scenario 4 (i.e. digester implemented in the Andean region). The amount of LPG replaced by biogas was calculated considering the biogas production and the lower caloric values of both fuels (Castro et al., 2017a, 2017b). Similarly, the synthetic fertiliser used in the previous scenarios is partially replaced by the digestate in scenarios 2 and 4. In these scenarios, the amount of synthetic fertiliser replaced by the digestate was determined considering the digestates nutrients content (Castro et al., 2017a, 2017b) and nutrients replacement values (i.e. 65% for N and 100% for P and K) (de Vries et al., 2012). Fugitive CH_4 emissions from leaks were considered as low as 5% of biogas production, since the digesters were supposed to be well-maintained (Bruun et al., 2014). As for LPG combustion, direct indoor emissions from biogas combustion were determined using emissions rates from previous studies (i.e. CO_2 (biogenic): 1444 g/kg_{biogas}; CO (biogenic): 1.9 g/kg_{biogas}; CH_4 (fossil): 1.0 g/kg_{biogas}; NMVOC: 0.6 g/kg_{biogas}; NO_X: 0.9 g/kg_{biogas}; N_2O: 0.09 g/kg_{biogas}; PM2.5: 0 g/kg_{biogas}; PM10: 0.5 g/kg_{biogas}; SO_2: 0.05 g/kg_{biogas}) (Sfez et al., 2017; Sharma and Nema, 2013; USEPA, 2000). Emissions rates for the estimation of direct emissions to air and soil (i.e. nutrients leaching) from digestate application on agricultural land were the same as for the synthetic fertiliser (IPPC, 2006).

Background data (i.e. data of construction materials, LPG and fertiliser production and transportation) were obtained from the *Ecoinvent 3.1* database (Moreno-Ruiz et al., 2014; Weidema et al., 2013).

2.2.3 Impact assessment

Potential environmental impacts were calculated using the software *SimaPro® 8* (Pre-sustainability, 2014) and the ReCipe midpoint method (hierarchist approach) (Goedkoop et al., 2009). This analytical tool is in accordance with ISO 14040 standards (ISO, 2000). The characterisation phase was performed considering the following impact categories: Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Photochemical Oxidant Formation, Particulate Matter Formation, Metal Depletion, Fossil Depletion.

2.3. Sensitivity analysis

A sensitivity analysis was performed to evaluate the influence of the most relevant assumptions on the results. To this end, the following parameters were taken into account: LPG and synthetic fertiliser transportation in all scenarios; CH_4, NH_3 and N_2O emissions from manure storage in scenario 1 and 3; nutrients leaching from manure storage in scenario 1 and 3; direct indoor emissions from LPG combustion in all scenarios; NH_3 and N_2O emissions as well as nutrients leaching due to synthetic fertiliser application to soil in all scenarios; direct indoor emissions from biogas combustion in scenarios 2 and 4; fugitive CH_4 emissions from leaks in scenarios 2 and 4; NH_3 and N_2O emissions as well as nutrients leaching due to digestate application to soil in scenarios 2 and 4. These parameters were modified with an increment of −10%

and +10% and the results were recalculated while keeping the other parameters constant (Clavreul et al., 2012).

2.4 Economic assessment

The economic analysis was carried out taking into account the expenses for LPG, synthetic fertiliser, their transportation and the digesters capital cost. As mentioned above, the considered lifespan was 20 years for all materials, except for plastic which was reduced to 5 years (Pérez et al., 2014). Digesters depreciation was taken into account considering digesters lifespan in order to estimate and compare the overall expenses for cooking fuel and fertiliser per year in all scenarios.

3. Results and Discussion

3.1 Life Cycle Assessment

The potential environmental impacts associated with each scenario and referred to both FUs are shown in Figure 1 and Table 4.

Comparing the four alternatives, previous scenarios (scenarios 1 and 3) dominated in all impacts categories analysed, while both digesters scenarios (scenarios 2 and 4) showed similar environmental performance (Figure 1). In particular, the environmental impacts of the digesters scenarios were between 1.5 and 5 times lower than those of the previous scenarios for the considered impact categories. This means that digesters implementation helped reducing the environmental impacts associated with manure handling, fuel and fertiliser use in the small-scale farms by 10-80%, depending on the impact category. This was mainly due to the reduction of LPG and synthetic fertiliser consumption in the digesters scenarios (scenarios 2 and 4). These results were in accordance with previous studies which assessed the environmental benefits of small-scale masonry digesters implemented in rural areas of different Asian and African countries (Lansche et al., 2017; Sfez et al., 2017; Vu et al., 2015; Wang et al., 2018). In the case of the previous scenarios (scenarios 1 and 3), the contribution of both LPG and synthetic fertiliser production, transportation and use accounted for 50-75% and 25-45% of the total impact in the Climate Change and Photochemical Oxidant Formation impact categories, respectively. In the same impact categories, digesters scenarios (scenarios 2 and 4) were mainly influenced by synthetic fertiliser production as well as air emissions due to its application to the agricultural soil (around 70% of the total impact). On the contrary, the contribution of biogas losses and combustion to the overall impact ranged between 15 and 20% in the same impact categories and for both scenarios. Indeed, previous studies showed that more than half of the impact on Climate Change was due to processes located outside the small-scale farms, where synthetic fertiliser is produced (Sfez et al., 2017). Regarding Terrestrial Acidification, Marine Eutrophication and Particulate Matter Formation potentials, the impact was mainly due to air emissions from fertiliser and digestate application (55-90% of the total impact), fertiliser production and transportation (10-25% of the total impact) and air emissions from manure storage (10-12% of the total impact) in all the considered scenarios. This was in accordance with the results obtained in a previous research that observed environmental advantage in these impact categories due to the use of digestate as a replacement for mineral fertilisers (Lansche et al., 2017). Concerning Freshwater Eutrophication potential, the life-cycle was almost entirely influenced by nutrients leaching from synthetic fertiliser application to soil (>90% of the total impact) in all the scenarios considered. Similarly, the impact was almost entirely caused by LPG and synthetic fertiliser production (>95%) in ozone depletion, metal depletion and fossil depletion impact categories. In all scenarios, LPG and synthetic fertiliser transportation had a negligible impact (<2% of the total impact) on all considered impact categories.

According to the results presented in Table 4, the potential environmental impacts of the digester implemented in the Caribbean region (mesophilic conditions) (scenario 2) were between 1.2 and 1.5 times lower than those of the digester implemented in the Andean region (psychrophilic conditions) (scenario 4) for the considered impact categories. This was mainly due to the higher biogas production in scenario 2, but also to the better quality of digestate (i.e. higher nutrients content) in this scenario (Castro et al., 2017a, 2017b). As mentioned above, the biogas production obtained in scenario 2 led to a total replacement of LPG, while in scenario 4 a small amount of LPG is still used for cooking (Tables 3). Moreover, the amount of synthetic fertiliser needed in scenario 2 was lower than that one required in scenario 4 (Table 3), due to the higher nutrients content in digestate. This may be due to the fact that digestate obtained in the former is less diluted than that one obtained in the latter. Indeed, since a longer HRT is required in the digester implemented in the Andean region (scenario 4), a higher amount of water is added to the feedstock. Besides, the digestate nutrients content also depend on the origin and composition of the feedstock and on feeding and management practices (Garfí et al., 2011b, 2011c). Thus, the higher nutrients content in the digestate from the digester implemented in the Caribbean region (scenario 2) compared to that one implemented in the Andean region (scenario 4), could be attributed to the feedstock characteristics. In both scenarios construction materials had a negligible impact (<5% of the total impact) on all considered impact categories. A previous study compared the environmental impacts of masonry and plastic tubular digesters implemented in the Peruvian Andes considering only their implementation (i.e. construction materials). The results showed that the plastic tubular digester caused the highest impact as a result of the relatively short lifespan of plastic materials (Pérez et al., 2014). Considering the results of the present study, which also considered the use of biogas and digestate, it can be concluded that the digester model does not strongly influence the environmental impacts. Thus, the selection of digester model should consider other criteria, such as (Ferrer-Martí et al., 2018): i) socio-economic aspects (i.e. beneficiaries' ability to pay, digester investment costs); ii) proper digester operation (i.e. water, manure and agricultural land availability); ii) digester reliability and durability (i.e. ease of digester construction, operation and maintenance, technology lifespan).

To sum up, biogas production and use for cooking contribute to reducing environmental impacts in small-scale Colombian farms. Although digestate use as organic fertiliser contributes to reducing environmental burdens, synthetic fertiliser production and application still account for the highest contribution (60-98%) to the overall impact in the digesters scenarios. Indeed, the digestate only covers around 15% of the fertiliser needs in small-scale farms. Thus, in order to improve the environmental performance of low-cost digesters implemented in small-scale farms, digesters should be designed and operated to produce larger amount and a better quality digestate (i.e. higher nutrients content). Moreover, if the digester design and operation are mainly based on the required biogas production, composting the remaining manure which is not digested would contribute to replacing higher amounts of synthetic fertilizer.

3.2 Sensitivity analysis

The results of the sensitivity analysis indicated that the most sensitive inventory components (i.e. parameters which made the indicators variate by more than ±3%) are the following:

- CO_2 and NMVOC indoor emissions from LPG combustion in the Climate Change and Photochemical Oxidant Formation impact categories in scenario 1 and 3. A 10% increase in CO_2 and NMVOC emissions in both scenarios would increase these environmental indicators by around 5%.
- NH_3 emissions due to synthetic fertiliser application to soil in the Terrestrial Acidification, Marine Eutrophication, Particulate Matter Formation impact categories in all scenarios. In these cases, a 10% increase in these emissions would increase this indicator by 5-7% in all scenarios.
- NH_3 emissions due to digestate application to soil in the Terrestrial Acidification and Marine Eutrophication impact categories in scenarios 2. A 10% increase in these emissions would increase this indicator by around 3%.
- P emissions to soil due to synthetic fertiliser application in the Freshwater Eutrophication impact category in all scenarios. In this case, a 10% increase in P soil emissions would increase this indicator by around 9% in all scenarios.

In conclusion, the results were found to be sensitive to air and soil emissions from LPG, digestate and fertiliser use. However, the variation of these parameters did not change the conclusions of the study. In fact, digesters (current) scenarios always showed better environmental performance compared to the previous scenarios.

3.3 Economic assessment

Results of the economic analysis are shown in Table 5. Expenses associated with LPG and synthetic fertiliser purchase were higher for the small-scale farm located in the Andean region (scenario 3) compared to that one located in the Caribbean region (scenario 1) (Table 5). This was mainly due to the fact the LPG, synthetic fertiliser and their transportation costs are higher in the remoter areas of the Colombian Andes

(Castro et al., 2017a, 2017b). Moreover, around 60% of the expenses were due to LPG purchase and transportation in both scenarios.

Digester capital costs are slightly higher in scenario 4 than in scenario 2. Indeed, a larger amount of construction materials are needed for digester implementation in the Andean region (scenario 4), due to the higher HRT (i.e. digester volume) required in this area. However, the initial investment cost for digesters implementation is quite low in both scenarios, representing only around 30% of the total expenses. Indeed, it has been observed that if low-density polyethylene is used for the plastic bag, capital costs of digesters implementation is around 100-200 dollars (Garfí et al., 2016). Considering digesters depreciation, it can be noted that expenses associated with cooking fuel and fertiliser consumption were reduced by 80% in both scenarios thanks to digesters implementation. Thus, around 400 and 800 dollars per year are saved in the small-scale farms implemented in the Caribbean and Andean region, respectively. This is in accordance with previous studies which observed that the main economic benefits of low-cost digesters are associated with fuel and fertiliser savings. In Costa Rica, it was estimated that families saved around 400 dollars per year for propane thanks to biogas use (Garwood, 2010). In Mexico, families saved around 600 and 750 dollars per year for fuel (firewood which was purchased) and fertiliser, respectively (Garwood, 2010). In rural communities of the Peruvian Andes families saved around 50 dollars per year (about 1-2% of family annual income) by using digestate as fertiliser instead of compost (Garfí et al., 2012). Considering the results of this study, the initial investment for digesters implementation was recovered after less than 6 months in both cases.

Finally, low-cost digester implementation in small-scale Colombian farms helps improving the standard of living of rural families, by strongly reducing expenses associated with cooking fuel and fertiliser purchase (by 80%).

4. Conclusions

The implementation of low-cost digesters in small-scale Colombian farms contributed to reducing environmental impacts associated with manure handling, fuel and fertilizer use (by up to 80%, depending on the impact category), due to the reduction of LPG and synthetic fertilizer consumption. Environmental impacts were only slightly lower in the Caribbean region digester than in the Andean region one, meaning that low-cost digesters are an appropriate and environmentally friendly technology also at high altitude. Finally, low-cost digesters implementation may help improving the standard of living of rural families, by strongly reducing (by 80%) expenses associated with cooking fuel and fertilizer purchase.

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Table 1. Summary of the inventory for scenario 1 and 3: previous scenarios in the small-scale farms located in the Caribbean and Andean region, respectively. Values are referred to 1 kg of treated manure

Inputs	**Scenario 1 and 3**	**Units**
LPG production and transport		
Production	2.278E-02	kg
Transport	4.555E-01	kg km
Synthetic fertiliser production and transport		
N	4.658E+00	g
P_2O_5	9.589E+00	g
K_2O	2.192E+00	g
Transport N	9.315E-02	kg km
Transport P_2O_5	1.918E-01	kg km
Transport K_2O	4.384E-02	kg km
Outputs		
Direct air emissions from manure storage		
CH_4	6.600E-03	g
NH_3	1.958E-01	g
N_2O	2.350E-02	g
Direct soil emissions from manure storage		
N	3.133E-01	g
P	1.008E-01	g
K	1.444E+00	g
Direct indoor emissions from LPG combustion		
CO_2 (fossil)	7.026E+01	g
CO (fossil)	3.394E-01	g
CH_4 (fossil)	1.139E-03	g
NMVOC	4.282E-01	g
NO_X	6.833E-02	g
N_2O	3.416E-03	g
PM2.5	6.833E-03	g
PM10	2.505E-02	g
SO_2	0.000E+00	g
Direct air emissions from synthetic fertiliser application in the field		
NH_3	1.164E+00	g
N_2O	4.658E-02	g
Direct soil emissions from synthetic fertiliser application in the field		
N	9.315E-01	g
P	1.256E+00	g
K	9.057E-01	g

Table 2. Summary of the inventory for scenario 2 and 4: digesters (current) scenarios in the small-scale farms located in the Caribbean and Andean region, respectively. Values are referred to 1 kg of treated manure

Inputs	**Scenario 2**	**Scenario 4**	
Construction materials for digester implementation			
Plastic and accessories for biogas pipelines	7.020E-05	7.020E-05	kg
Bricks	2.880E-04	5.400E-04	kg
Cement	6.912E-05	1.296E-04	kg
Sand	6.720E-03	1.260E-02	kg
Metals	2.208E-05	4.140E-05	kg
Cookstove (clay)	1.980E-05	1.980E-05	kg
Polyethylene (biogas reactor and biogas reservoir)	5.728E-04	1.004E-03	kg
Water			
rainwater	1.176E+00	2.598E+00	L
LPG production and transport			
Production	0.000E+00	1.265E-03	kg
Transport	0.000E+00	2.531E-02	kg km
Synthetic fertiliser production and transport			
N	3.390E+00	4.179E+00	g
P_2O_5	8.544E+00	9.218E+00	g
K_2O	0.000E+00	0.000E+00	g
Transport N	6.779E-02	8.357E-02	kg km
Transport P_2O_5	1.709E-01	1.844E-01	kg km
Transport K_2O	0.000E+00	0.000E+00	kg km
Outputs			
Direct air emissions from biogas losses			
CH_4 biogenic	7.020E-04	6.630E-04	kg
Direct indoor emissions from biogas combustion			
CO_2 (biogenic)	3.119E+01	2.946E+01	g
CO (biogenic)	4.104E-02	3.876E-02	g
CH_4 (biogenic)	2.160E-02	2.040E-02	g
NMVOC	1.296E-02	1.224E-02	g
NO_X	1.944E-02	1.836E-02	g
N_2O	1.944E-03	1.836E-03	g
PM2.5	0.000E+00	0.000E+00	g
PM10	1.080E-02	1.020E-02	g
SO_2	1.080E-03	1.020E-03	g
Direct indoor emissions from LPG combustion			
CO_2 (fossil)	0.000E+00	3.904E+00	g
CO (fossil)	0.000E+00	1.885E-02	g
CH_4 (fossil)	0.000E+00	6.327E-05	g
NMVOC	0.000E+00	2.379E-02	g
NO_X	0.000E+00	3.796E-03	g
N_2O	0.000E+00	1.898E-04	g
PM2.5	0.000E+00	3.796E-04	g
PM10	0.000E+00	1.392E-03	g
SO_2	0.000E+00	0.000E+00	g
Direct air emissions from digestate application in the field			

NH_3	4.877E-01	1.842E-01	g
N_2O	1.951E-02	7.369E-03	g
Direct soil emissions from digestate application in the field			
N	5.072E-02	1.916E-02	g
P	7.761E-03	2.755E-03	g
K	1.668E-01	5.525E-01	g
Direct air emissions from synthetic fertiliser application in the field			
NH_3	8.474E-01	1.045E+00	g
N_2O	3.390E-02	4.179E-02	g
Direct soil emissions from synthetic fertiliser application in the field			
N	6.779E-01	8.357E-01	g
P	1.119E+00	1.208E+00	g
K	0.000E+00	0.000E+00	g

Table 3. Summary of the inventory for scenario 2 and 4: digesters (current) scenarios in the small-scale farms located in the Caribbean and Andean region, respectively. Values are referred to 1 m^3 of biogas

Inputs	**Scenario 2**	**Scenario 4**	
Construction materials for digester implementation			
Plastic and accessories for biogas pipelines	3.900E-03	4.129E-03	kg
Bricks	1.600E-02	3.176E-02	kg
Cement	3.840E-03	7.624E-03	kg
Sand	3.733E-01	7.412E-01	kg
Metals	1.227E-03	2.435E-03	kg
Cookstove (clay)	1.100E-03	1.165E-03	kg
Polyethylene (biogas reactor and biogas reservoir)	3.182E-02	5.906E-02	kg
Water			
rainwater	6.534E+01	1.528E+02	L
LPG production and transport			
Production	0.000E+00	7.443E-02	kg
Transport	0.000E+00	1.489E+00	kg km
Synthetic fertiliser production and transport			
N	1.883E+02	2.458E+02	g
P_2O_5	4.746E+02	5.422E+02	g
K_2O	0.000E+00	0.000E+00	g
Transport N	3.766E+00	4.916E+00	kg km
Transport P_2O_5	9.493E+00	1.084E+01	kg km
Transport K_2O	0.000E+00	0.000E+00	kg km
Outputs			
Direct air emissions from biogas losses			
CH_4 biogenic	3.900E-02	3.900E-02	kg
Direct indoor emissions from biogas combustion			
CO_2 (biogenic)	1.733E+03	1.733E+03	g
CO (biogenic)	2.280E+00	2.280E+00	g
CH_4 (biogenic)	1.200E+00	1.200E+00	g
NMVOC	7.200E-01	7.200E-01	g
NO_X	1.080E+00	1.080E+00	g
N_2O	1.080E-01	1.080E-01	g
PM2.5	0.000E+00	0.000E+00	g
PM10	6.000E-01	6.000E-01	g
SO_2	6.000E-02	6.000E-02	g
Direct indoor emissions from LPG combustion			
CO_2 (fossil)	0.000E+00	2.296E+02	g
CO (fossil)	0.000E+00	1.109E+00	g
CH_4 (fossil)	0.000E+00	3.722E-03	g
NMVOC	0.000E+00	1.399E+00	g
NO_X	0.000E+00	2.233E-01	g
N_2O	0.000E+00	1.116E-02	g
PM2.5	0.000E+00	2.233E-02	g
PM10	0.000E+00	8.187E-02	g
SO_2	0.000E+00	0.000E+00	g
Direct air emissions from digestate application in the			

field			
NH_3	2.709E+01	1.084E+01	g
N_2O	1.084E+00	4.334E-01	g
Direct soil emissions from digestate application in the field			
N	2.818E+00	1.127E+00	g
P	4.312E-01	1.620E-01	g
K	9.267E+00	3.250E+01	g
Direct air emissions from synthetic fertiliser application in the field			
NH_3	4.708E+01	6.145E+01	g
N_2O	1.883E+00	2.458E+00	g
Direct soil emissions from synthetic fertiliser application in the field			
N	3.766E+01	4.916E+01	g
P	6.218E+01	7.103E+01	g
K	0.000E+00	0.000E+00	g

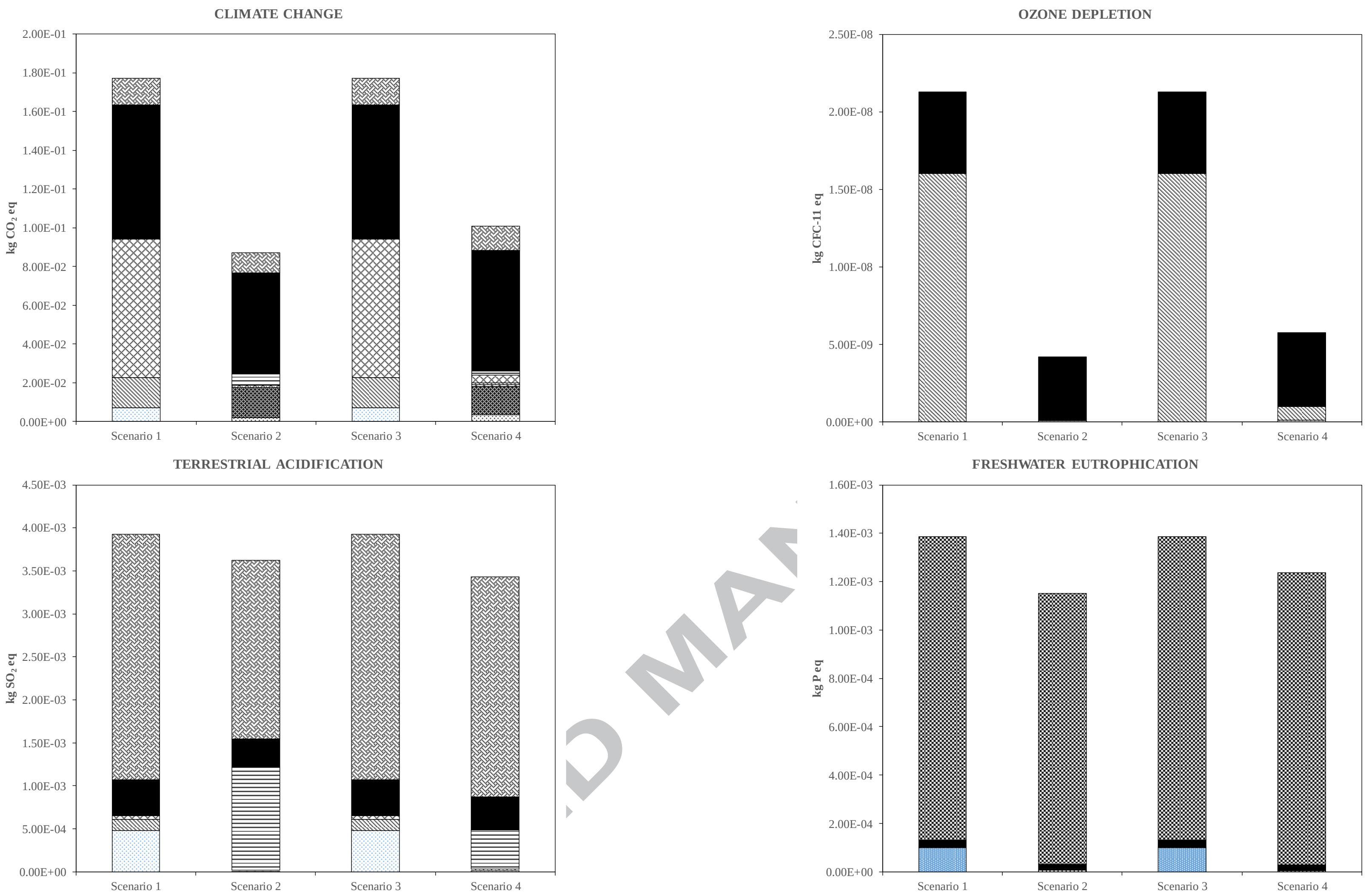
Table 4. Potential environmental impacts for the digesters (current) scenarios in the small-scale farms located in the Caribbean and Andean region (scenario 2 and 4, respectively). Values are referred to 1 m^3 of biogas

Impact category	**Unit**	**Scenario 2**	**Scenario 4**
Climate change	kg CO_2 eq	4.83E+00	5.93E+00
Ozone depletion	kg CFC-11 eq	2.33E-07	3.40E-07
Terrestrial acidification	kg SO_2 eq	2.01E-01	2.02E-01
Freshwater eutrophication	kg P eq	6.40E-02	7.28E-02
Marine eutrophication	kg N eq	7.96E-03	8.08E-03
Photochemical oxidant formation	kg NMVOC	1.10E-02	1.53E-02
Particulate matter formation	kg PM10 eq	3.22E-02	3.36E-02
Metal depletion	kg Fe eq	2.69E-01	3.33E-01
Fossil depletion	kg oil eq	6.47E-01	9.22E-01

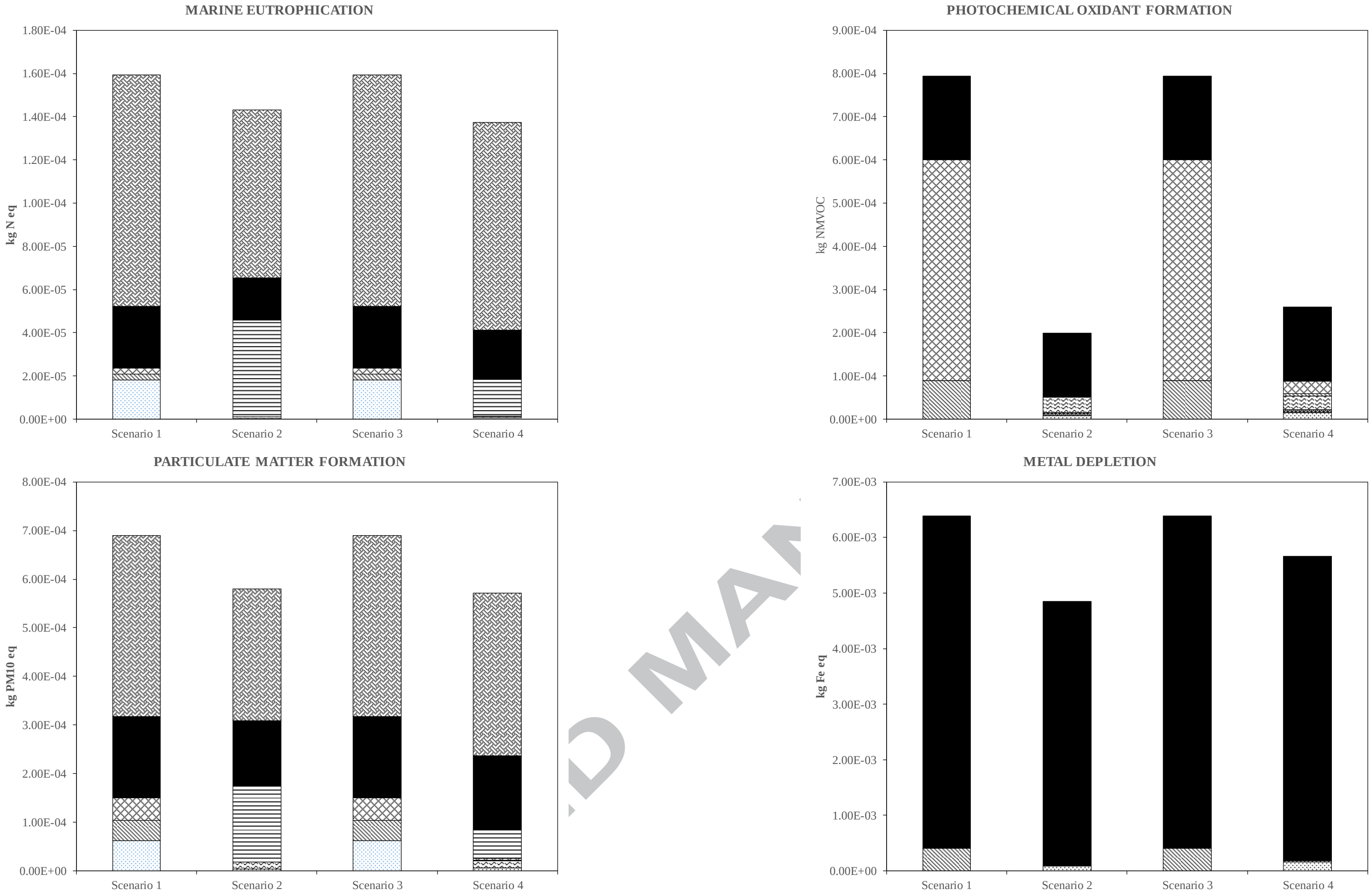
Table 5. Results of the economic analysis for the scenarios considered

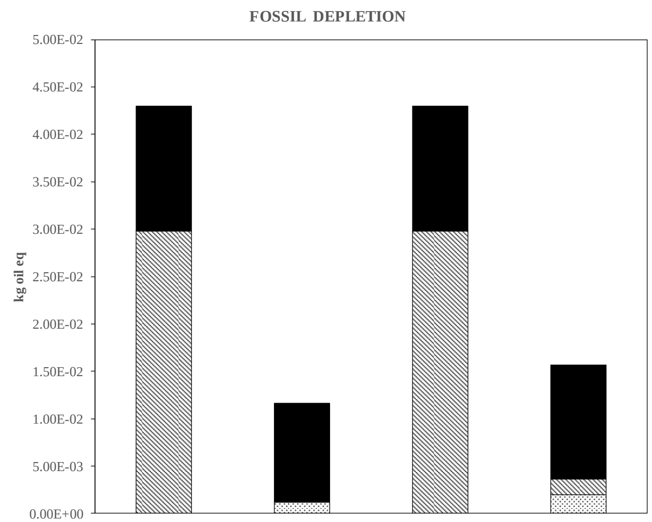
	Units	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Digester					
Capital cost	$	-	190	-	205
Digester depreciation	$ year^{-1}	-	38	-	41
LPG					
Purchase	$ year^{-1}	360	-	600	30
Transportation	$ year^{-1}	120	-	300	15
Synthetic fertiliser					
Purchase	$ year^{-1} ha^{-1}	111	80	111	92
Transportation	$ year^{-1}	10	10	25	25
Total expenses	$ year^{-1}	601	128	1036	203

Note: scenario 1: previous scenario in the small-scale farm located in the Caribbean region; scenario 2: previous scenario in the small-scale farm located in the Andean region; scenario 3: digester (current) scenario in the small-scale farm located in the Caribbean region; scenario 4: digester (current) scenario in the small-scale farm located in the Andean region



CLIMATE CHANGE
kg CO2 eq
2.00E-01
1.80E-01
1.60E-01
1.40E-01
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
OZONE DEPLETION
kg CFC-11 eq
2.50E-08
2.00E-08
1.50E-08
1.00E-08
5.00E-09
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
TERRESTRIAL ACIDIFICATION
kg SO2 eq
4.50E-03
4.00E-03
3.50E-03
3.00E-03
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
FRESHWATER EUTROPHICATION
kg P eq
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4


MARINE EUTROPHICATION
kg N eq
1.80E-04
1.60E-04
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
PHOTOCHEMICAL OXIDANT FORMATION
kg NMVOC
9.00E-04
8.00E-04
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
PARTICULATE MATTER FORMATION
kg PM10 eq
8.00E-04
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4
METAL DEPLETION
kg Fe eq
7.00E-03
6.00E-03
5.00E-03
4.00E-03
3.00E-03
2.00E-03
1.00E-03
0.00E+00
Scenario 1
Scenario 2
Scenario 3
Scenario 4



Direct air emissions from manure storage

Direct soil emissions from manure storage

LPG production and transport

Direct indoor emissions from LPG combustion

Fertilizer production and transport

Direct air emissions from fertilizer application in the field

Direct soil emissions from fertilizer application in the field

Construction materials (digesters)

Rainwater

Direct air emissions from biogas losses

Direct indoor emissions from biogas combustion

Direct air emissions from digestate application in the field

Direct soil emissions from digestate application in the field

Figure 1. Potential environmental impacts for all scenarios: previous scenario in the small-scale farm located in the Caribbean region (scenario 1); previous scenario in the small-scale farm located in the Andean region (scenario 2); digester (current) scenario in the small-scale farm located

in the Caribbean region (scenario 3); digester (current) scenario in the small-scale farm located in the Andean region (scenario 4). Values are referred to 1 kg of treated manure.

Highlights

- Life cycle assessment of low-cost digesters in small-scale farms was performed
- Biogas and digestate replaced liquefied petroleum gas and synthetic fertilizer
- Scenarios previous to low-cost digesters implementation were also considered
- Digesters reduced environmental impacts by up to 80%
- Digesters reduced expenses associated with fuel and fertilizer purchase by 80%